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Muckle++ Protocol: An experimental analysis of Provably Quantum-Secure integration of QKD and PQC

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Agenda

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- Motivation for a Hybrid PQC-QKD scheme
- NIST PQC Competition Update
- Muckle++ Protocol: A hybrid key exchange protocol
  - Ingredients
  - Design choices
  - Superior Security
- Implementation platform
- Performance Results
- Results
- Outlook

AQuaSeC

Agile Quantum Safe Communications (AQuaSeC)

QUANTUM COMMUNICATIONS HUB

EPSRC funded Quantum Comms Hub

Averting the Quantum threat (2 ways)

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The physical approach is QKD (Quantum Key Distribution)

- Ensures *information theoretic security*
- Security based on the laws of quantum mechanics
- Demonstrated good levels of maturity in the last decade with improved key generation rates, extending longer distances, improved scalability.

\+ Information theoretic security

− Large changes in Infrastructure and hardware, range limitations, expensive deployment

The classical approach is PQC (Post Quantum Cryptography)

- PQC refers to cryptographic schemes, thought to be secure even against quantum computers.
- Other names include *Quantum-resistant Cryptography, Quantum-Safe Cryptography*
- Major types of Post quantum cryptography include Lattice based cryptography; Code based cryptography, etc.

\+ Work on classical computers used today

− Lower maturity, standardization, research on going

Muckle[1]++ Protocol: A Hybrid Key Exchange Protocol

- A Hybrid Key exchange protocol combining the following three
  - Classical public key algorithms (**CKEM**)
  - Post Quantum KEMs (**QKEM**)
  - Quantum Key Distribution (**QKD**)

- A physical unclonable function (**PUF**) is used for device authentication
  - Providing additional layer of security

- A modular design
  - increased efficiency for different security parameters

- A working implementation with a commercial QKD, an FPGA and a server is undertaken

- This work started under **AQuaSec** (Agile Quantum Safe Communications), funded by Innovate UK.
  - Funded Period: Nov 18 - Aug 21

- A paper is submitted to **PRX Quantum** (under review)

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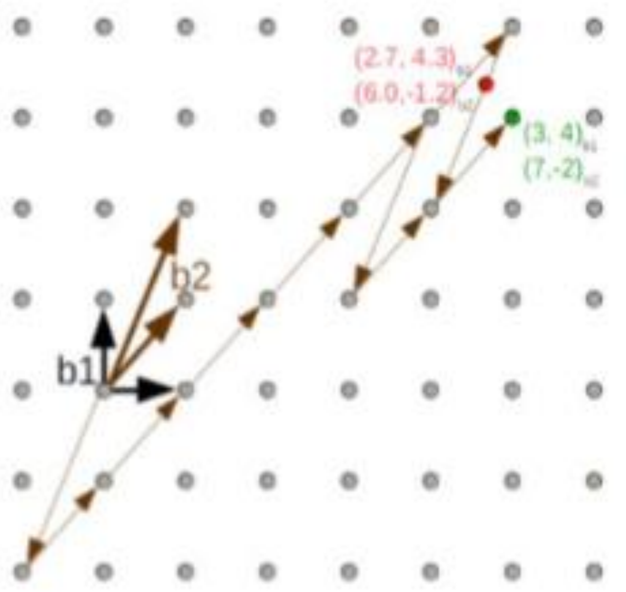
[1] Dowling, Benjamin, et. Al. "Many a mickle makes a muckle: A framework for provably quantum-secure hybrid key exchange" *PQCrypto* 2020.

Muckle++: The Ingredients- Post Quantum Cryptography (Why choose lattices)

Lattice-based Cryptography is emerging as a promising PQC candidate.

- **Security**: Based on are well-studied theoretical foundations – with no known attacks
- **Flexibility**: Enable constructions beyond PKE, signatures, e.g., Identity based encryption (IBE), Attribute-based encryption (ABE), Fully homomorphic encryption (FHE).
- **Efficiency**: Simple underlying arithmetic operations, efficient on a range of diverse platforms.
  - *VPN strong Swan* supports post-quantum mode (NTRU and BLISS schemes)
  - *Google* successfully experimented with New Hope key exchange (a Lattice-based Cryptography KEM scheme)



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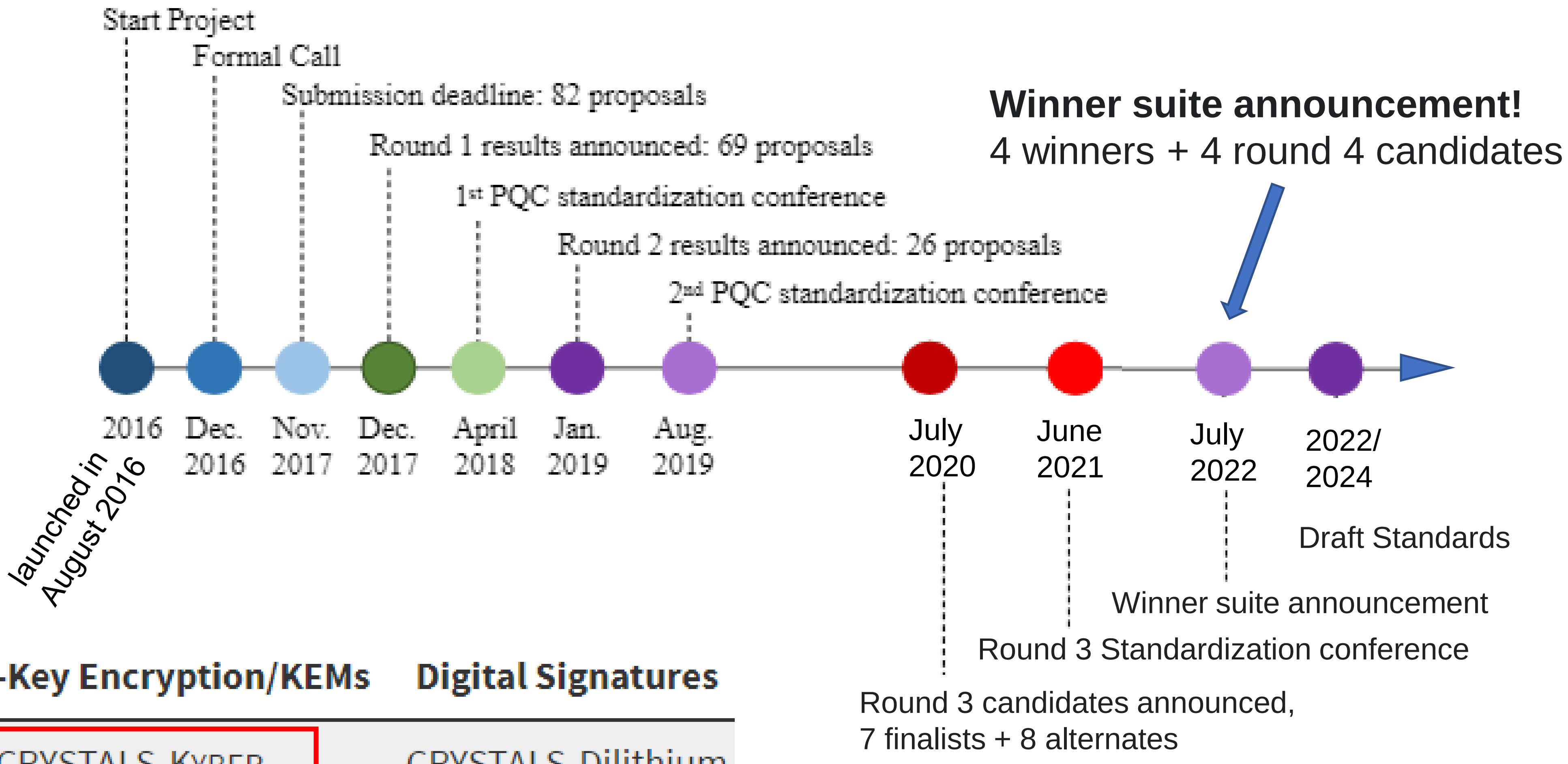
US NIST - Call for Quantum-Resistant Cryptographic Algorithms for new public-key cryptography standards (https://csrc.nist.gov/Projects/Post-Quantum-Cryptography)



For standardization

Public-Key Encryption/KEMs	Digital Signatures
CRYSTALS-KYBER	CRYSTALS-Dilithium
	FALCON
	SPHINCS+

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Muckle++ Protocol: A hybrid key exchange protocol

- A Hybrid Key exchange protocol combining the following
  - Classical public key algorithms (**CKEM**)
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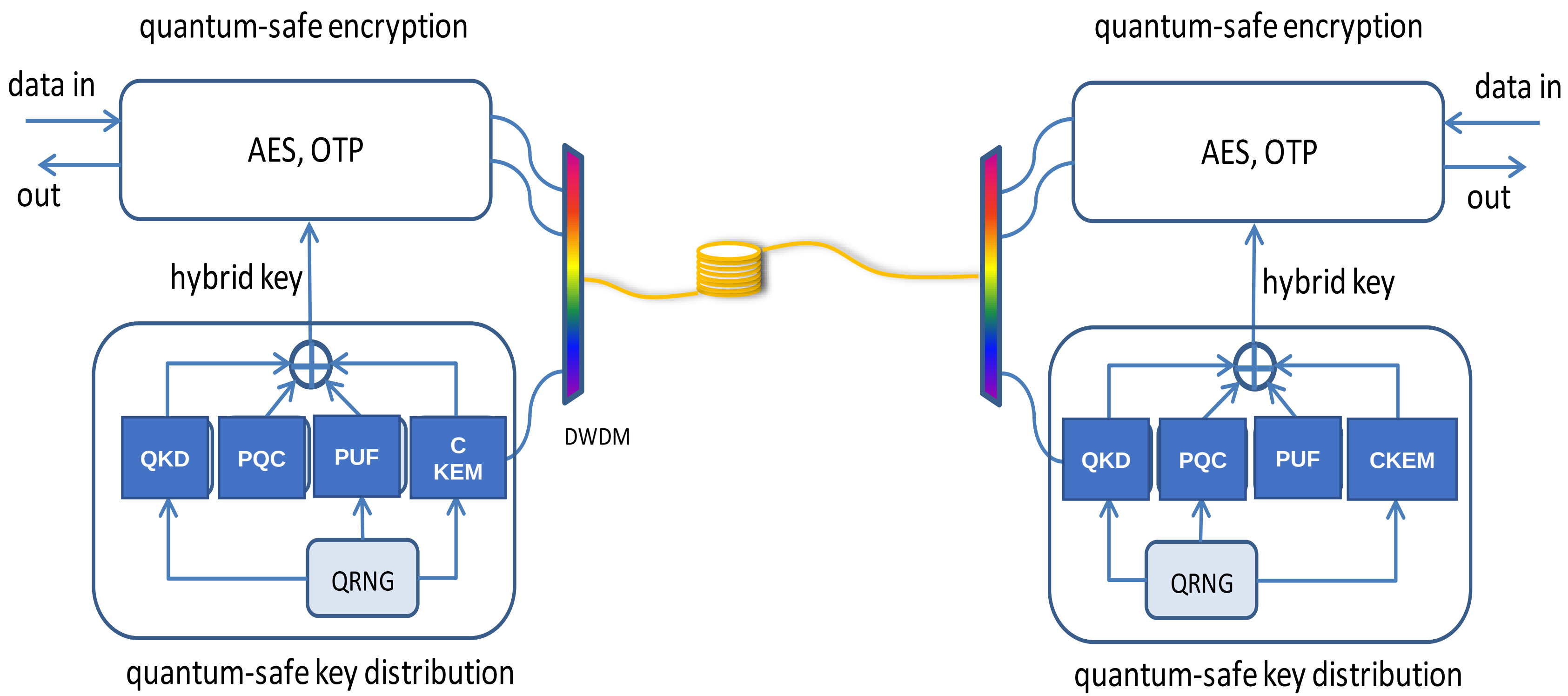
  - Quantum Key Distribution (**QKD**)
  - A physical unclonable function (**PUF**)



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Muckle++: The Ingredients

- Classical public key algorithms
  - **KEM**: Ephemeral Elliptic Curve Diffie- Hellman Elliptic curve (Elliptic curve curve25519)
  - ECDSA (Elliptic curve NIST P-256)

- Quantum Key Distribution (**QKD**)
  - Commercial grade QKD system[1]
  - Quantum bit error rates below 3%
  - QKD secure key rates above 3 Mb/s over a 10-dB loss channel.

- FPGA-based physical unclonable functions (**PUF**s)
  - Based on ‘Ultra-compact and robust FPGA-based PUF identification generator’ [2]

- Post Quantum Cryptography
  - **QKEM**: CRYSTALS-Kyber (n=3), mid range security
  - QSignature: Falcon (n=512, q=12289)

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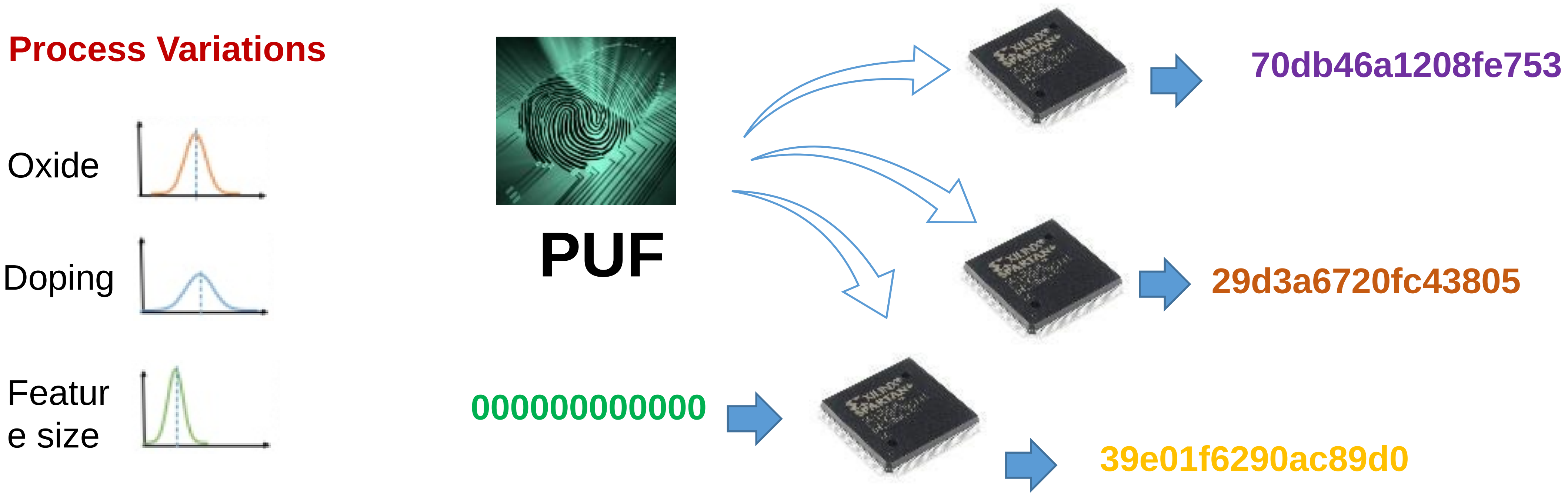
[1] Yuan, Zhiliang, et al. "10-Mb/s quantum key distribution." *Journal of Lightwave Technology* 36.16 (2018): 3427-3433..
[2] Gu, Chongyan, and Maire O'Neill. "Ultra-compact and robust FPGA-based PUF identification generator." *2015 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2015.

Muckle++: The Ingredients- Physically Unclonable Function (PUF)

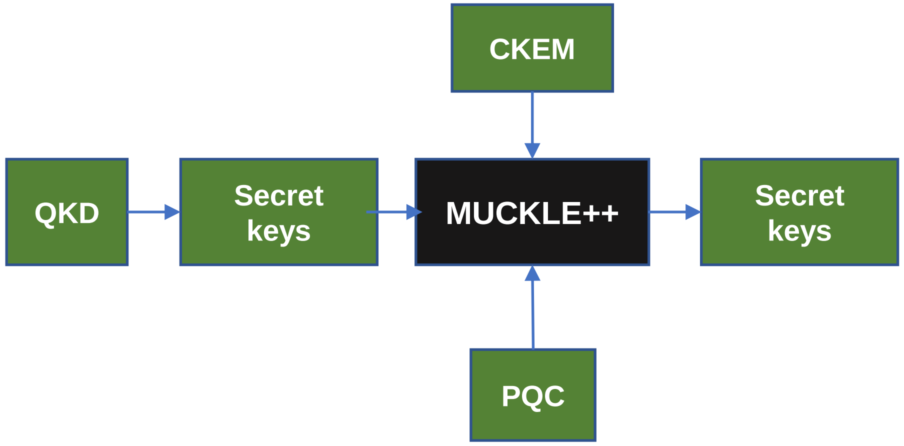
A PUF is a digital circuit that uses manufacturing process variations to generate a unique digital fingerprint.

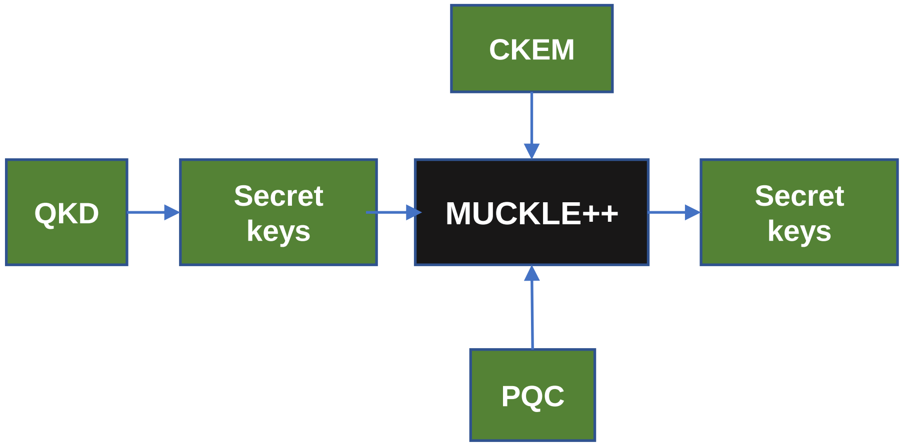


No two chips should give the same response when supplied with the same challenge.

Muckle++: Better Security Properties

- **Breakdown Resilience:** The key exchange protocol remains secure, provided at least any one of three ingredients: QKD, classical key exchange and quantum resistant key exchange, remains secure.





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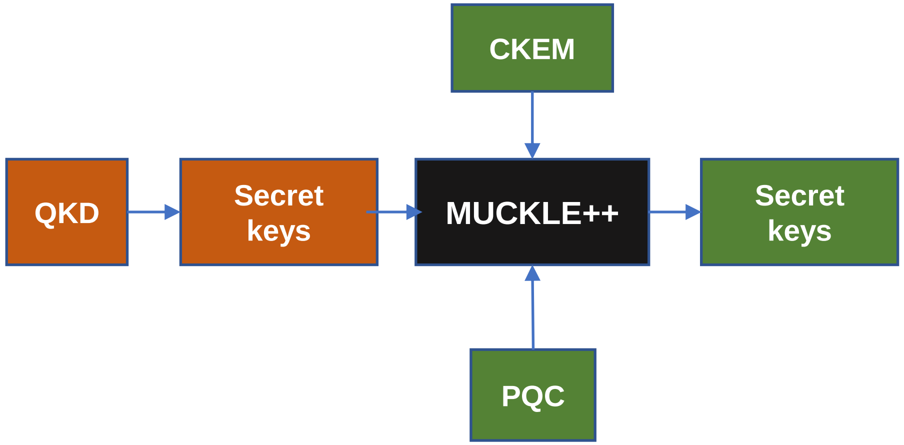

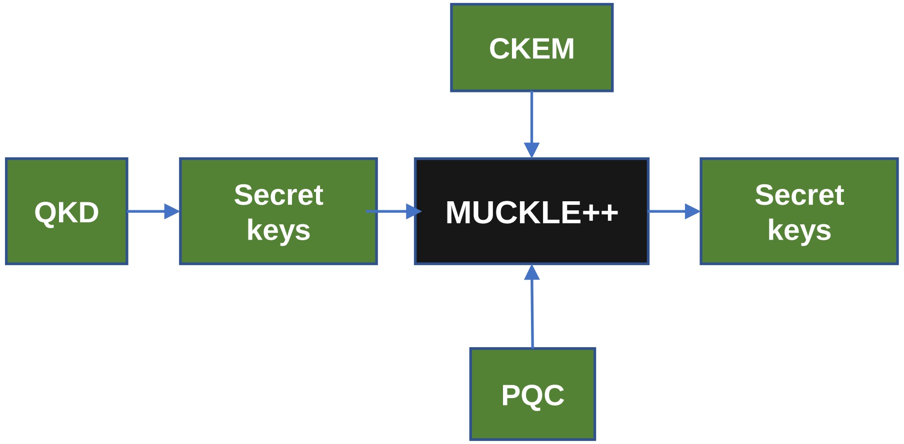

Still secure against Quantum attacks ☺

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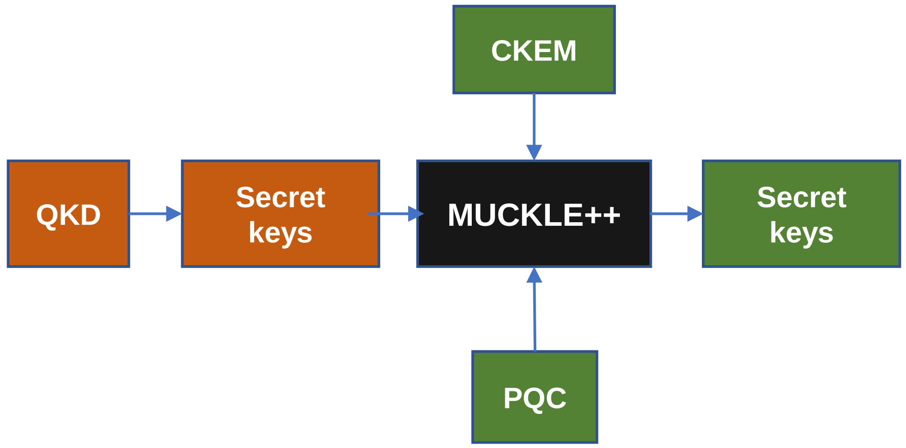

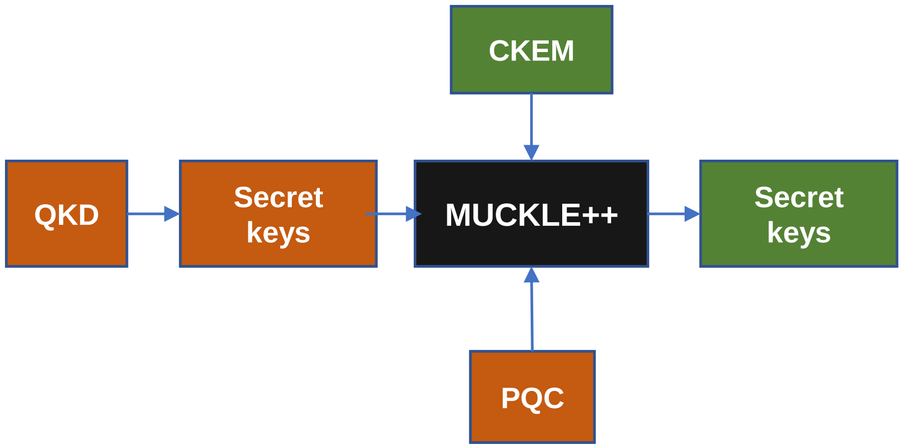

Still secure against Quantum attacks ☺

Only secure against classical attackers ☹

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Muckle++: Better Security Properties

- **Breakdown Resilience:** The key exchange protocol remains secure, provided at least any one of three ingredients: QKD, classical key exchange and quantum resistant key exchange, remains secure.

- **Post-compromise Security[1]:** The secret state allows for post-compromise security, that is, security can be recovered in the event of session keys being leaked.

- **Forward Security**: is guaranteed, ensuring that a security breach will not affect the security of previous keys.

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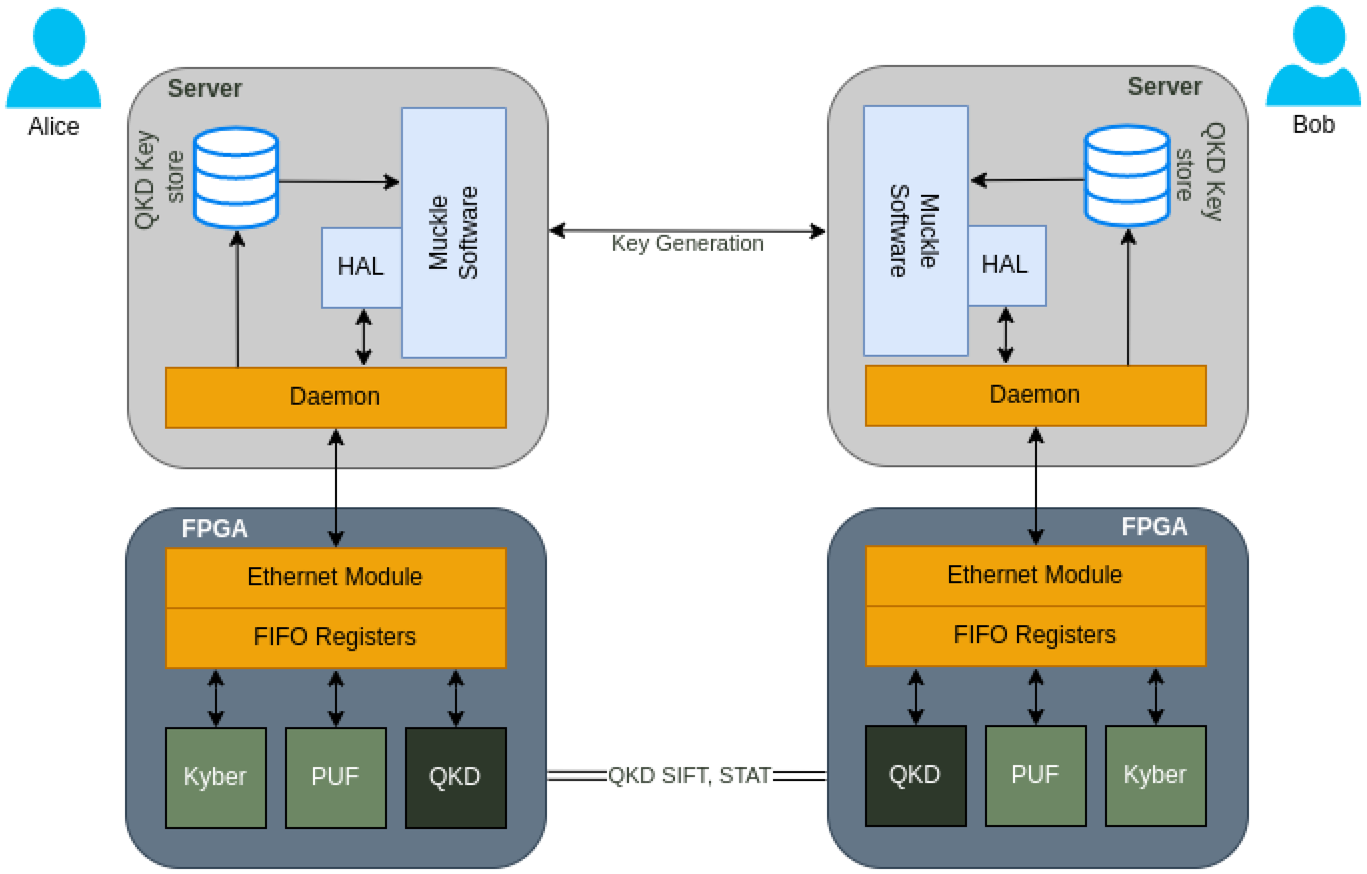
[1] Cohn-Gordon, et. al.. "On post-compromise security." *2016 IEEE 29th Computer Security Foundations Symposium (CSF)*. IEEE, 2016.

Muckle++: Results

- Insecure communication channel across servers
- Muckle++ software runs on the server with a hardware abstraction layer (HAL)
- A custom Daemon enables communication with hardware IP, running on an FPGA connected via Ethernet.
- Xilinx 7-series FPGA device used



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Muckle++: Performance

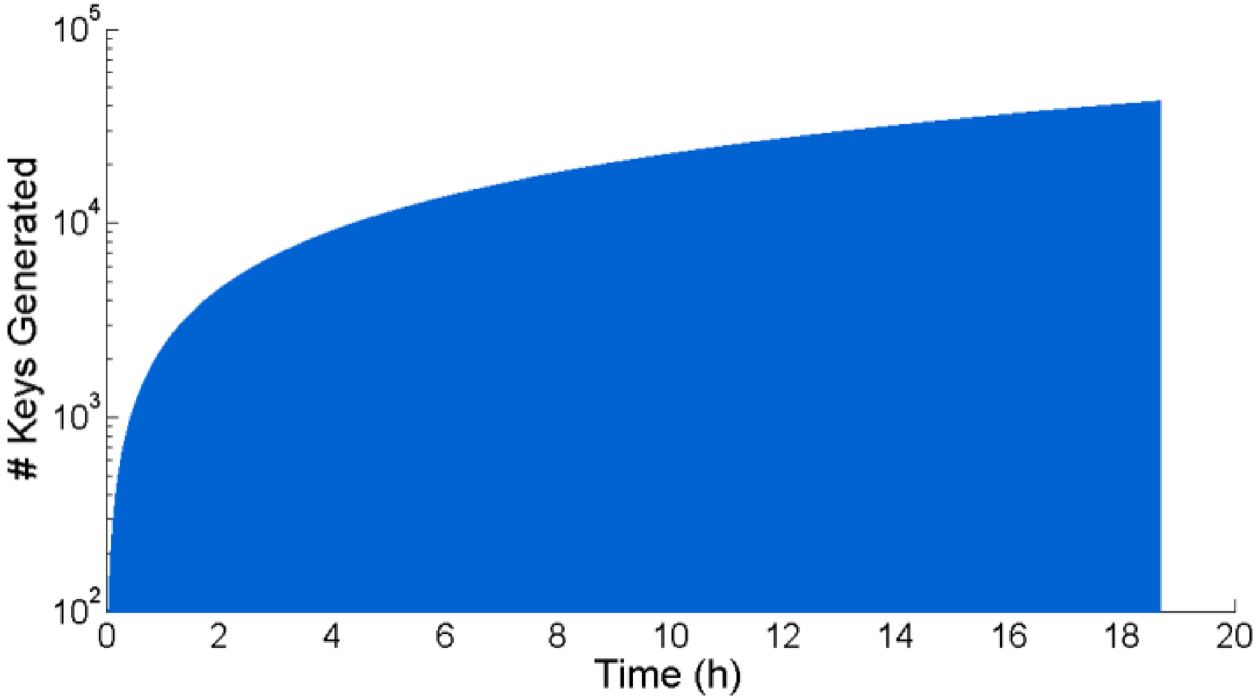
- Muckle++ protocol was run on a commercial server and connected via Ethernet to a Xilinx 7-series FPGA.

- Required time to readout the PUF response in minimal, with < 200 clock cycles required including error correction

- Running the entire system to continuously generate fresh key material led to stable operation, with one **hybrid-quantum-safe key** per second and run times > 20 hours, as shown below

Resource	Kyber	PUF
LUT	17339	4347
LUTRAM	2962	0
FF	7060	5404
BRAM	8.5	0
DSP	43	0

CRYSTALS-Kyber + PUFArea Requirements on 7-series Xilinx FPGA



	Latency (cc^a)	Latency (μs)	Operations per second
Load Secret Key	609	17.4	57471
Encapsulation	19458	555.94	1798
Decapsulation	27746	792.74	1261

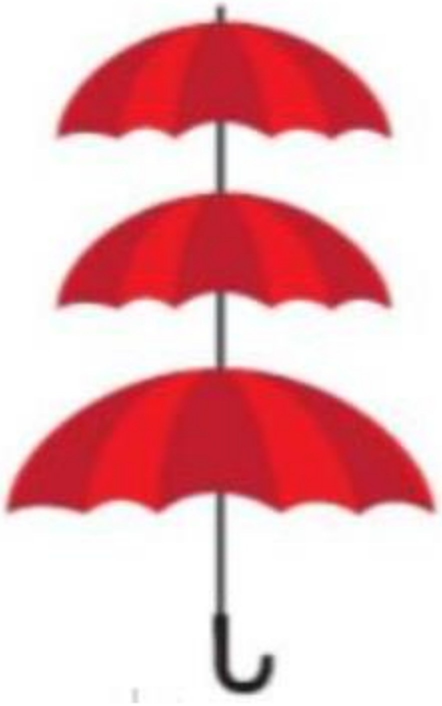
[a] clock cycles.

CRYSTALS-Kyber Performance at 35 MHz

Muckle++: Contributions

Provably Quantum-Secure integration of QKD and PQC in an authenticated key exchange protocol.

- **Post compromise security:** Security is compromised only if all the three layers of security are broken
  - Classical public key algorithms (**CKEM**)
  - Post Quantum KEMs (**QKEM**)
  - Quantum Key Distribution (**QKD**)
- **Flexibility (Modular design)**: Different building blocks can be easily swapped to allow for increased efficiency or different security parameters
- **Efficiency**:
  - Combines the best of the two worlds, integrating QKD into more practical PQC systems
  - Developed the first working implementation of the system.



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Muckle++: Outlook

Our work aims to pave the way for future endeavours exploiting both quantum and post-quantum technologies.

- **Efficiency:** leveraging a full hardware implementation of the Muckle++ protocol, taking advantage of FPGA-based QKD post-processing for better efficiency.
- **Investigating further use-cases:** Greater range of potential use case scenarios and applications would provide useful contributions to on-going standardisation activities
- **Vulnerability Analysis:** Undertaking vulnerability analysis of the physical security of integrated PQC-QKD designs including side channel analysis attacks and/or fault attacks.
    - *Several relevant PhD positions open currently at Queens University*. Spread the word around.

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Thank you

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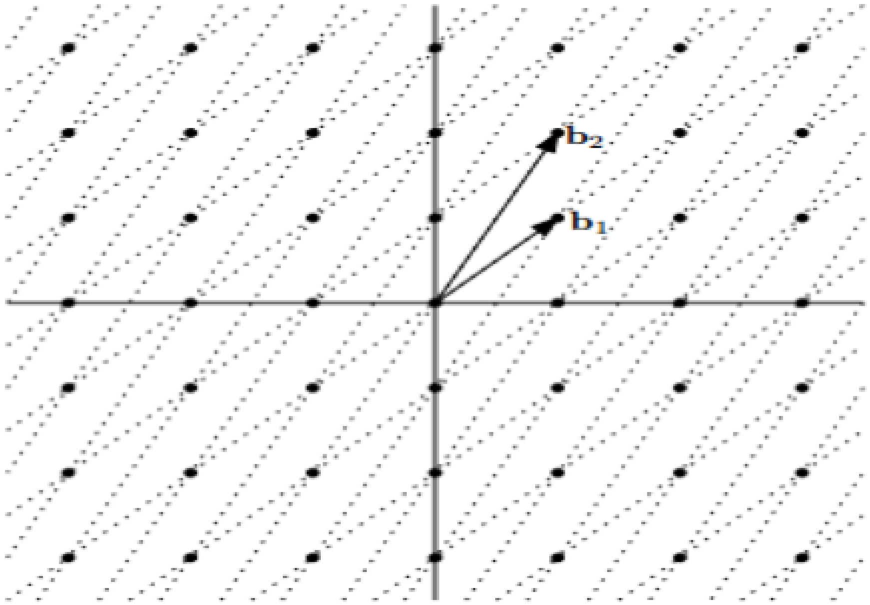
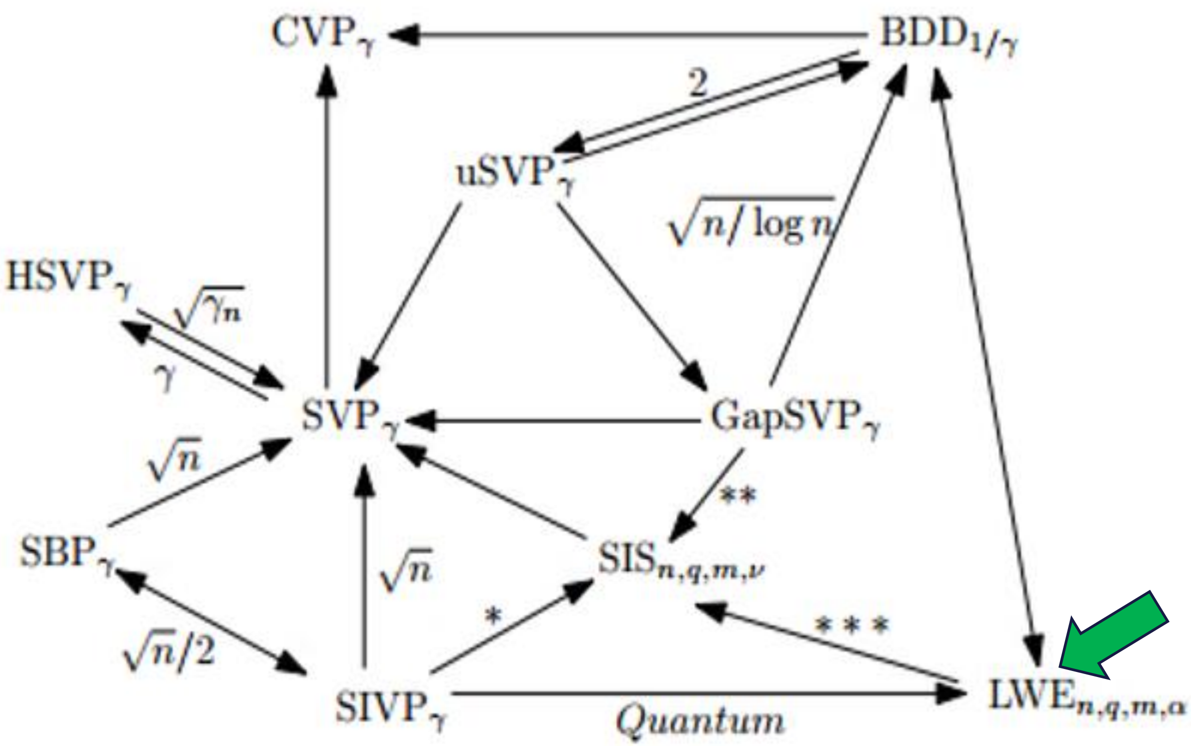
Introduction to Lattice based Cryptography

- A lattice is defined by a **basis** of **n** vectors. The lattice points can be defined by a linear combination of these basis vectors with integer coefficients

$$\boldsymbol{v} = a_1\boldsymbol{b_1} + a_2\boldsymbol{b_2} + \cdots + a_n\boldsymbol{b_n}$$

Lattice ➡ Hard problems ➡ Quantum-resilient cryptographic problems





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Learning with Errors problem (LWE)

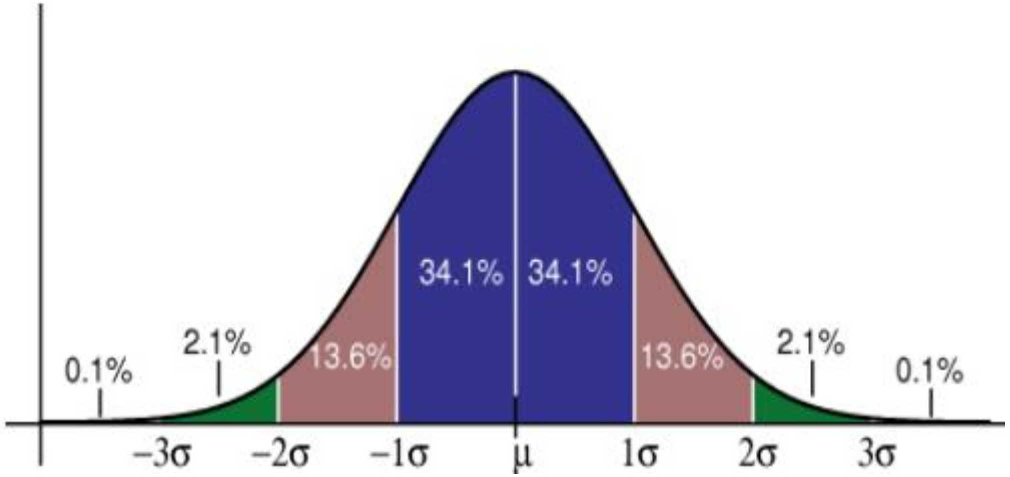
The LWE problem is defined as:

$$As + e = b \bmod q$$

Given (A, b), find s.

4 main interdependent parameters:

- Matrix A has dimension $n \times m$,
- Error vector e is chosen from a Gaussian distribution of ∂,
- All working in a field modulus q



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Learning with Errors problem (LWE)

Solving of a system of linear equations

secret

$$\underset{\mathbb{Z}_{13}^{7\times 4}}{\begin{bmatrix} 4 & 1 & 11 & 10 \\ 5 & 5 & 9 & 53 \\ 3 & 9 & 0 & 10 \\ 1 & 3 & 3 & 2 \\ 12 & 7 & 3 & 4 \\ 6 & 5 & 11 & 4 \\ 3 & 3 & 5 & 0 \end{bmatrix}} \times \underset{\mathbb{Z}_{13}^{4\times 1}}{\begin{bmatrix} 6 \\ 9 \\ 11 \\ 11 \end{bmatrix}} = \underset{\mathbb{Z}_{13}^{7\times 1}}{\begin{bmatrix} 4 \\ 8 \\ 1 \\ 10 \\ 4 \\ 12 \\ 9 \end{bmatrix}}$$

Use Gaussian elimination

The LWE problem is defined as:

$$\boldsymbol{As} + \boldsymbol{e} = \boldsymbol{b} \bmod q$$

Given $(\boldsymbol{A},\boldsymbol{b})$, find $\boldsymbol{s}$.

Blue is given; Find (learn) **red** => Solve linear system

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(slides taken from talk by Douglas Stebila at RWC'15)

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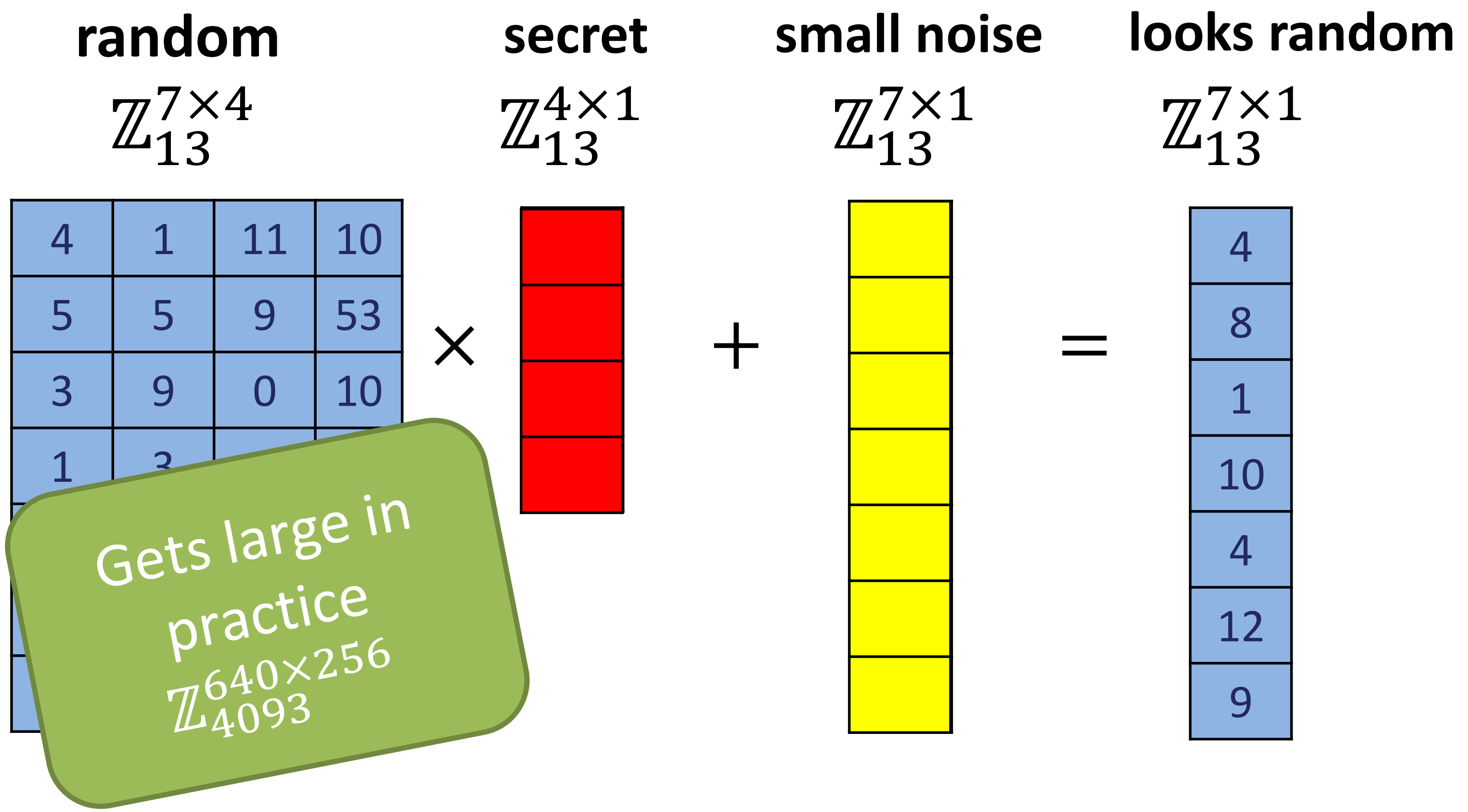

Parameter sets	n	p	σ	$\lvert \boldsymbol{c}_1, \boldsymbol{c}_2 \rvert$	|sk|	|pk|	security
(256,4093,8.35 [LP11]	256	4093	~4.5	6,144	1,792	6,144	~106 bits
(256,7681,11.32) [GFSBH12]	256	7681	~4.8	6,656	1,792	6,656	~106 bits
(512,12289,12.18) [GFSBH12]	512	12289	~4.9	14,336	3,584	14,336	~256 bits

(slides taken from talk by Douglas Stebila at RWC'15)